Search for High Mass Higgs at WW and ZZ Channels using ATLAS Run-I Data

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Introduction

04/07/2012

- After the discovery of a SM Higgs boson around 125 GeV, there are still some open questions in SM (e.g. Higgs self-energy)
- Several BSM models predict heavy neutral scalars

8 TeV,
20.3 fb-1 data

ZZ paper : http://arxiv.org/abs/1507.05930
WW paper : http://arxiv.org/abs/1509.00389

Signal models	WW	ZZ
Narrow Width Approximation (NWA)	✔	✔
Complex Pole Scheme (CPS)	✔	
Two Higgs Doublet Model (2HDM)		✔
Intermediate-width (IW)	✔	

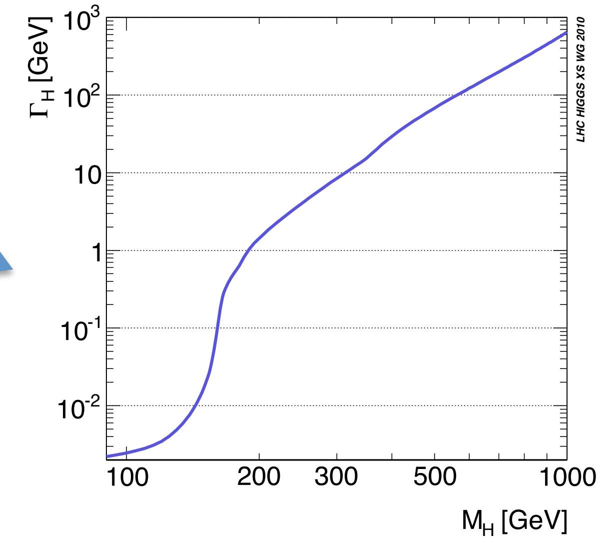
Signal Models (NWA, IW)

- Narrow Width Approximation (NWA)
  - Use width of SM Higgs boson at 125 GeV (4.07 MeV)
  - Do not need to worry about interference between signal and background
  - Can go to region beyond 1 TeV

- Intermediate-width (IW)
  - Motivated by (ElectroWeak Singlet) EWS model
  - Use the signal width between NWA and SM-like width
  - The cross section and partial width are scaled with different values . Use BR from SM prediction
  - Interference effects are taken into account as CPS model

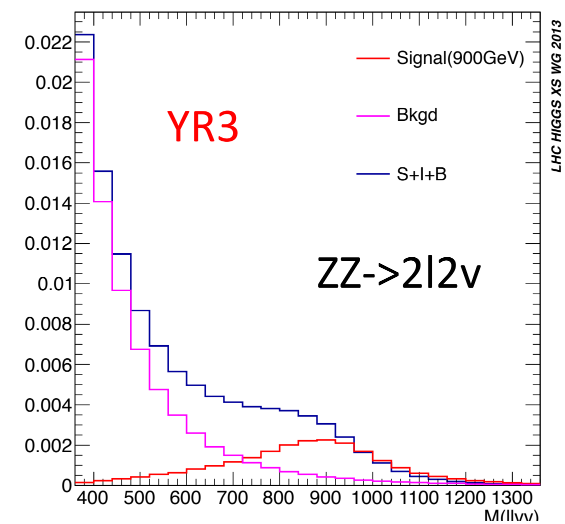
Complex Pole Scheme (CPS)

- Use SM-like width :



How to account interference

- CPS samples are generated via Powheg Box without any interference
- ggF : use MCFM to generate S+B+I, B and S samples and derive the weights
- VBF : use REPOLO (REweighting POwheg events at Leading Order) to derive the weights
- Apply those weights to CPS Powheg samples



CERN-2013-004 : Fig 124

Two Higgs Doublet Model (2HDM)

- Add another doublet to Higgs sector
  - Five physical Higgs bosons : two CP-even h and H; one CP-odd, A and two charged $H^{\pm}$
- Free parameters :
  - Higgs boson masses : mh, mH, mA, $mH^{\pm}$
  - $\tan\beta$: ratio of the vacuum expectation values between the two doublet
  - α : the mixing angle between the two CP-even states h and H
  - m^2_{12} : the parameter to mix the two doublets
- Different types of 2HDM:
  - Type I : one Higgs doublet couples to vector bosons and the other couples to fermions (fermiophobic)
  - Type II : one doublet couples to up-type quarks, and the other couples to down-type quarks and leptons (MSSM like)

Analyses Strategies Overview I

- The interference between signal and continuum background is done by reweighting
  - ‘Large width’ signal searches can not go beyond 1 TeV
- The signal searches span from 140 GeV to 1500 GeV
  - Low mass region : more background, multi-leptons final states have better sensitivity
  - High mass region : low background, high branch ratio final states tend to have better sensitivity generally
  - Have to use different analysis strategy different mass region. For example, *(->next)*

Analyses Strategies Overview II

Channels	Range	Production modes	
WW->lvlv	CPS : 220 GeV – 1 TeV NWA : 300 GeV – 1.5 TeV IW : 200 GeV – 1 TeV	ggF, VBF	
WW->lvqq		ggF, VBF	signal mass dependent selections; Use large-R jets
ZZ->4l	140 GeV – 1 TeV	ggF, VBF, VH	Good for low mass
ZZ->llqq	200 GeV – 1 TeV	ggF, VBF	merged jet region for mH > 700 GeV (still using anti-kt R=0.4)
ZZ->llvv	240 GeV – 1 TeV	ggF, VBF	
ZZ->vvqq	400 GeV – 1 TeV	ggF	

WW->lvlv

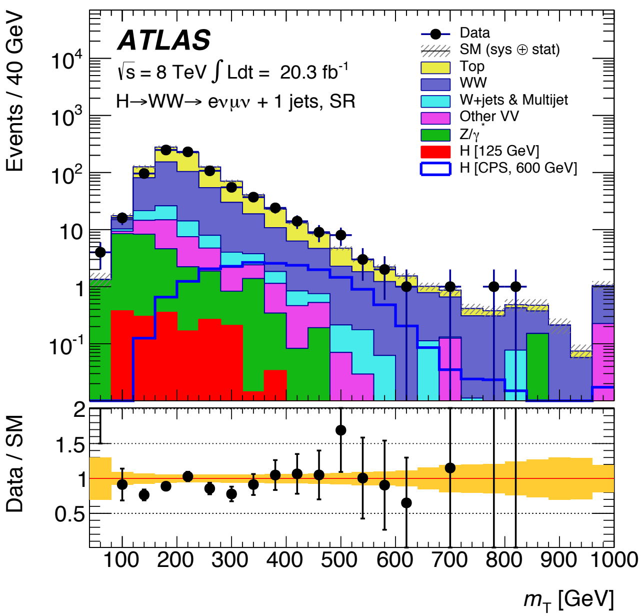
- Two leptons (e/mu) and two neutrinos.
- Low background due to number of leptons.
- Poor mass resolution due to the neutrinos
- Separate events into 0, 1 and ≥2 jets
- Use Top control regions and WW control regions to constrain background in signal regions

Use transverse mass as discriminant :

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}|^2},$$

Main background :
- WW
- Top

arXiv:1509.00389



WW->lvqq

- Larger branching ratio. More sensitive at higher mass region
- Use full mass (m_{lvjj}) as discriminant (p_v^Z is constrained by W mass)
- Include large-R jets to have better signal efficiency
- Use signal mass dependent selections

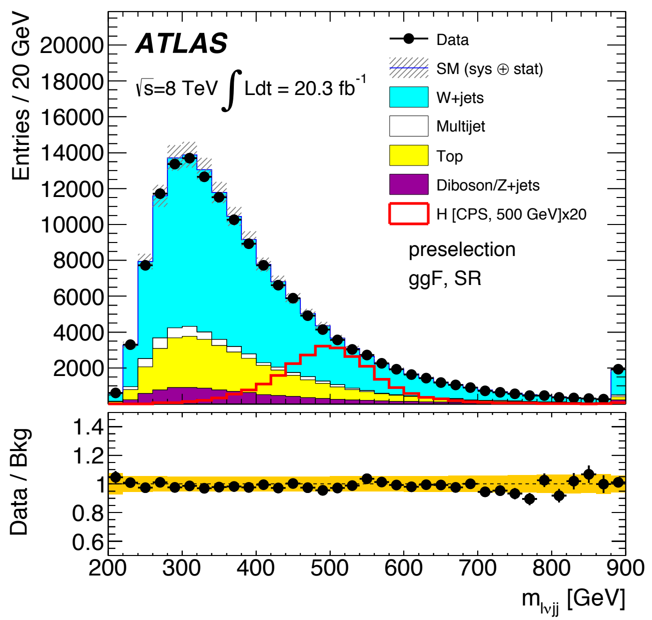
Cambridge/Achen (CA) algorithm with R=1.2

Standard mass drop filter algorithm applied ($N_{subjets} = 3$, $y_{cut} < 0.09$, $\mu_{frac} = 0.67$, $R_{min} = 0.3$) ; $p_T^{jet} > 100$ GeV, $|\eta^{jet}| < 1.2$ JHEP09 (2013) 076, arXiv:1306.4945

Main background :

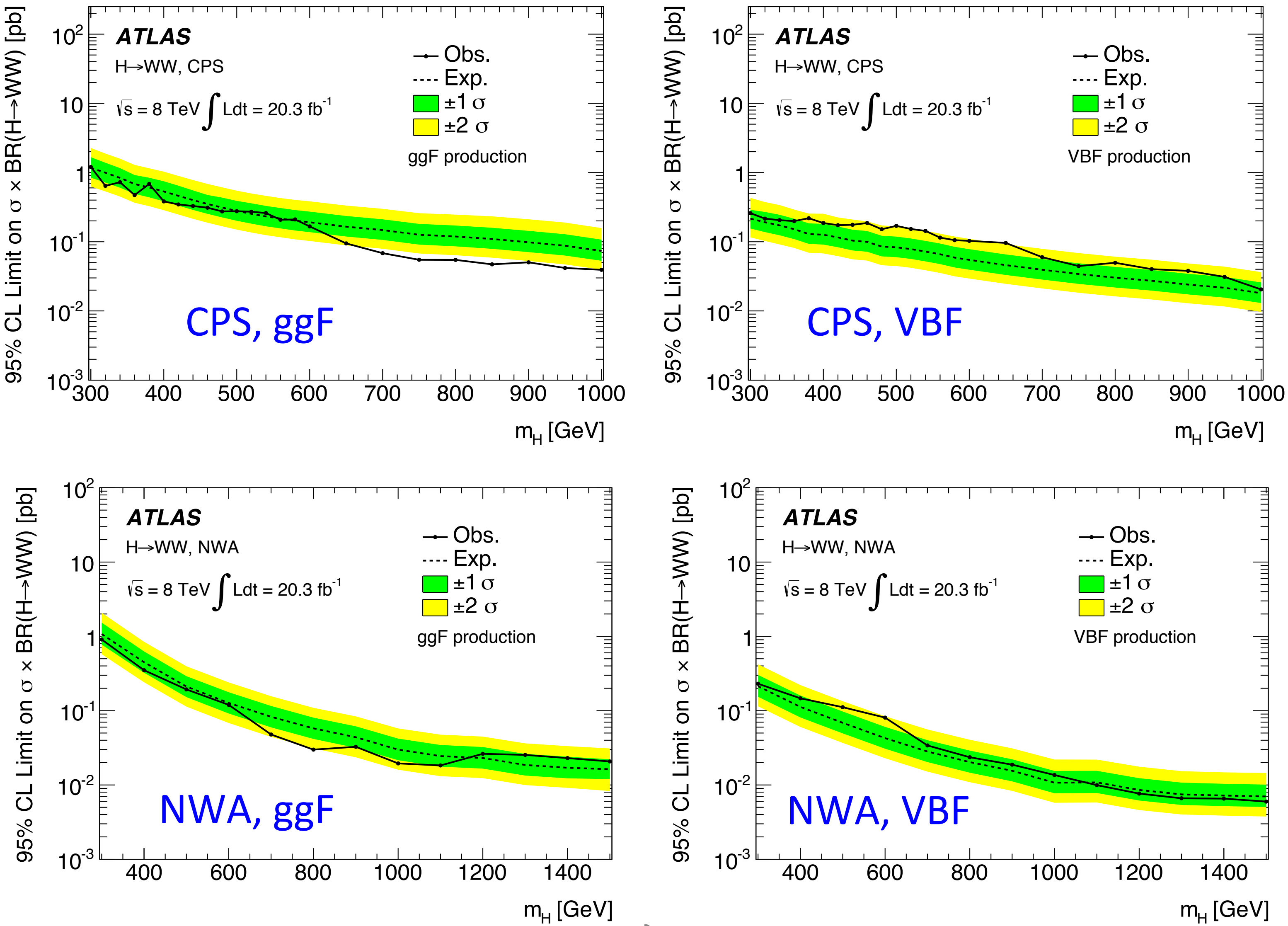
- Wjets
- Top

arXiv:1509.00389



WW Results

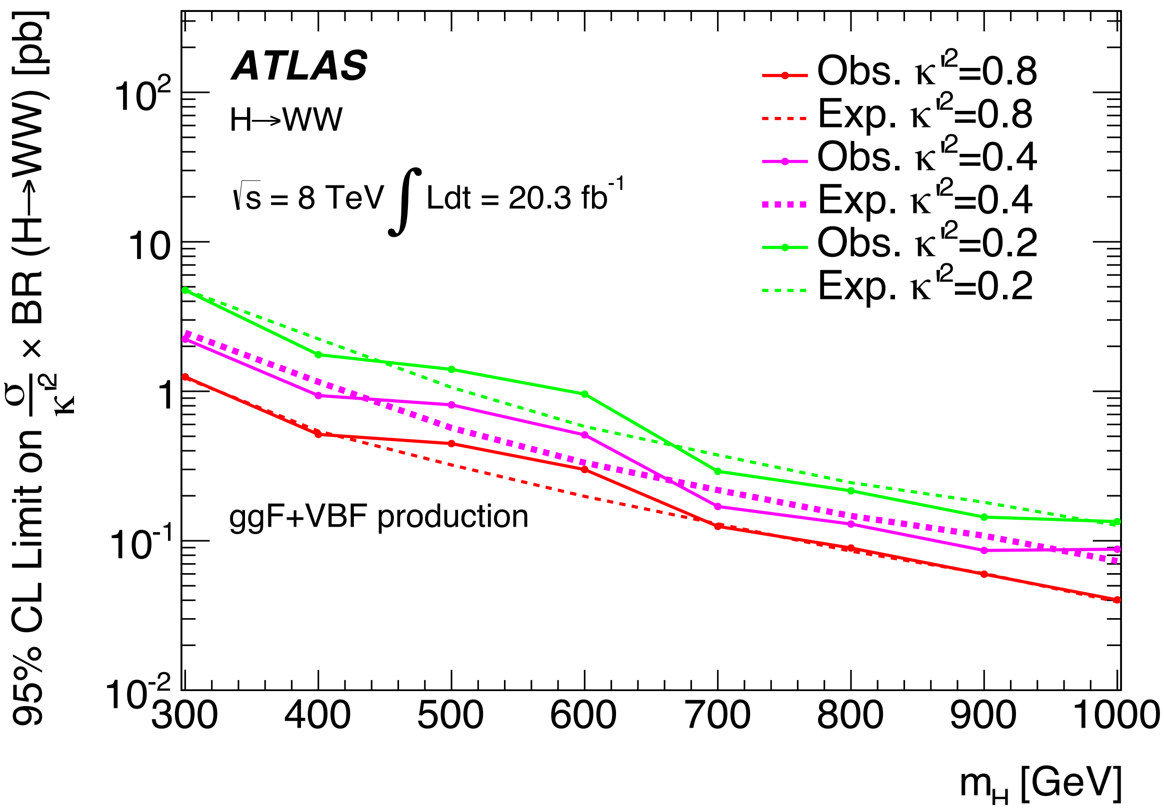
arXiv:1509.00389



WW Results

Limits for intermediate-width scenarios with $\Gamma\_H = \{0.2, 0.4, 0.8\} \times \Gamma\_H^{SM}$

arXiv:1509.00389



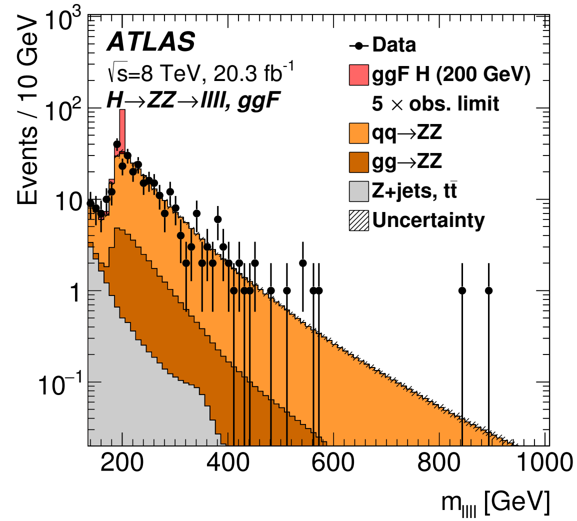
In order to display the different curves in the plots, limits are shown in σ/κ'2 ×BR

ZZ Analyses

ZZ->4l

- Good mass resolution. Can use full mass (m_{4l})
- Dominant background : continuum ZZ, Zjets

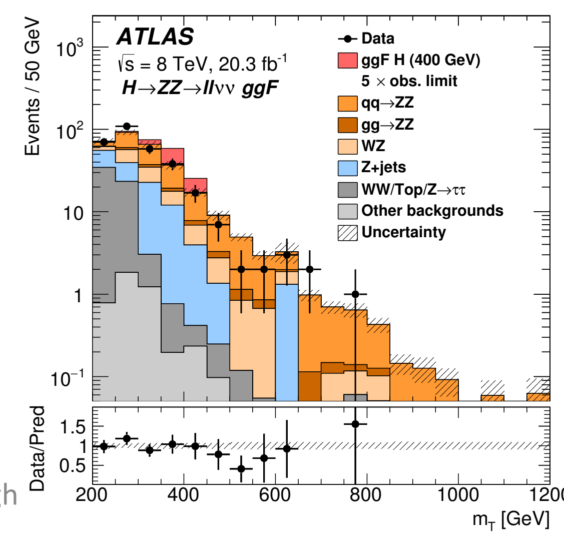
arXiv:1507.05930



ZZ->llvv

$$(m_{\mathrm{T}}^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + \left|p_{\mathrm{T}}^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|E_{\mathrm{T}}^{\mathrm{miss}}\right|^2} \right)^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2 .$$

arXiv:1507.05930

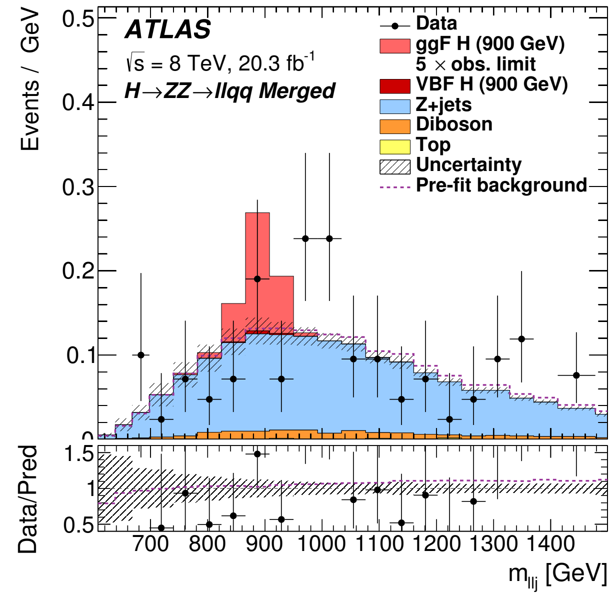


ZZ Analyses

ZZ->llqq

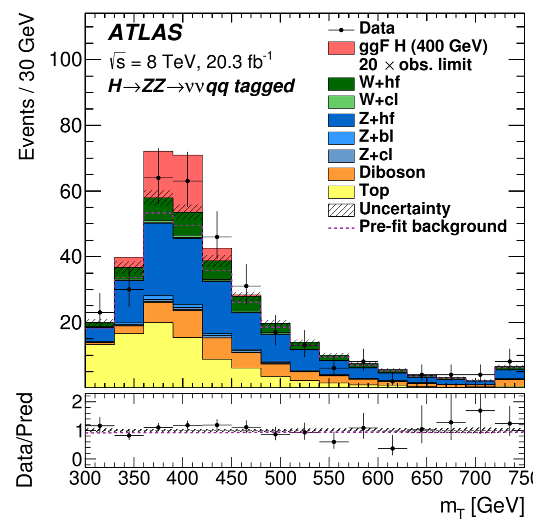
- Use full mass (m_{llqq}) as discriminant variable
- Merged jet region for mH > 700 GeV (still using anti-kt R=0.4)
- Require mll and mJ to be consistent with *Z* mass
- Main background : Z+jets

arXiv:1507.05930



ZZ->vvqq

- MET trigger
- Transverse mass as discriminant
- Main background : Z+jets, top

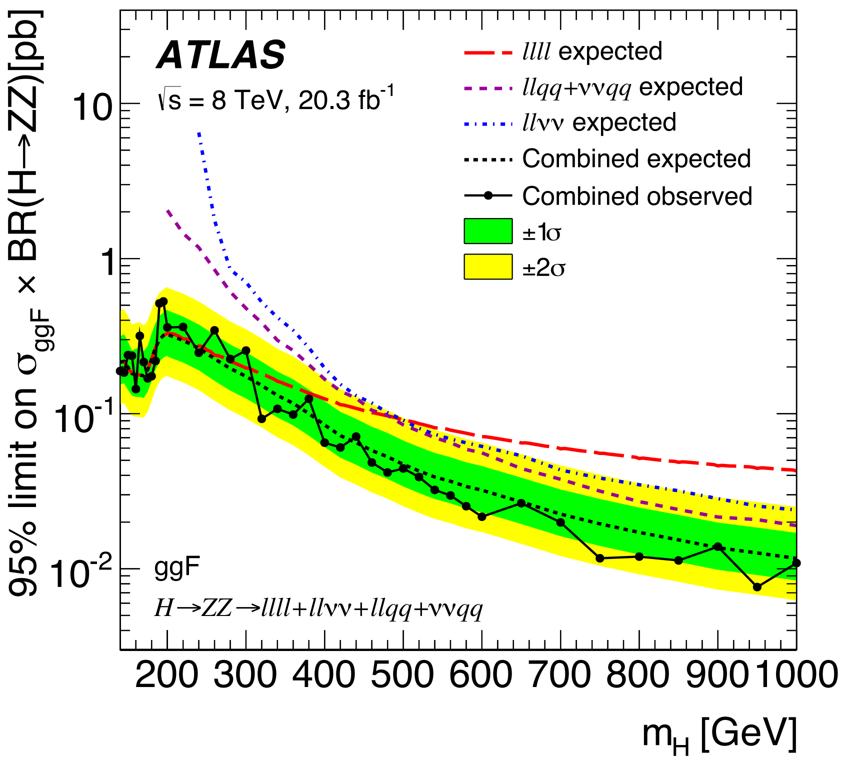


arXiv:1507.05930

ZZ Results - NWA

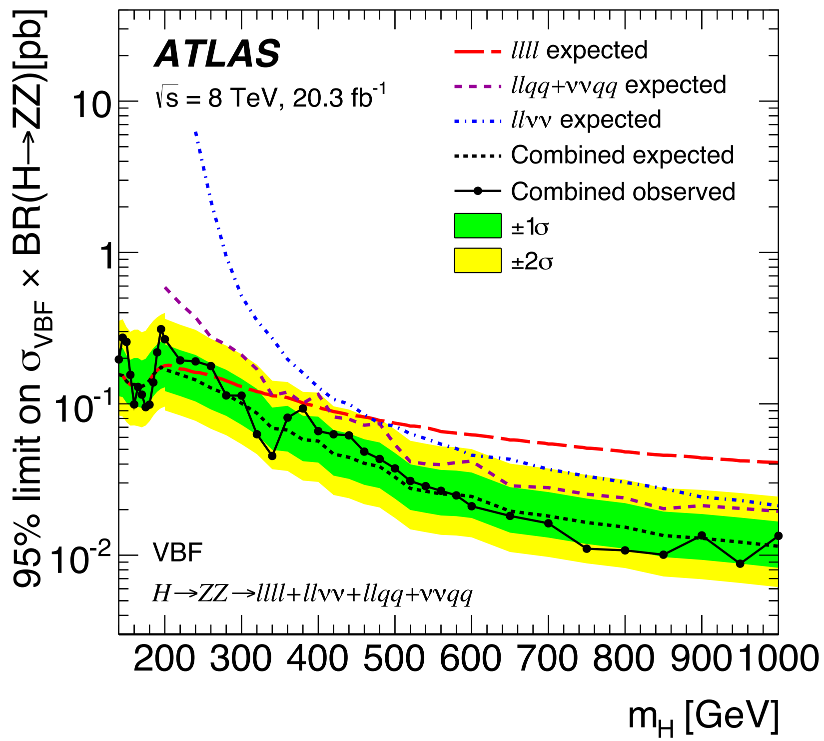
ggF

arXiv:1507.05930



VBF

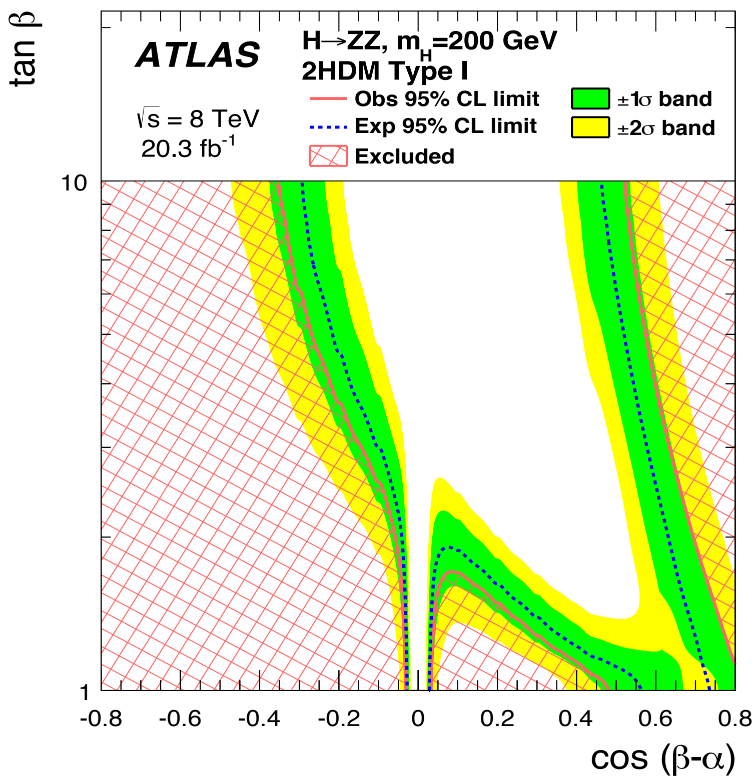
arXiv:1507.05930



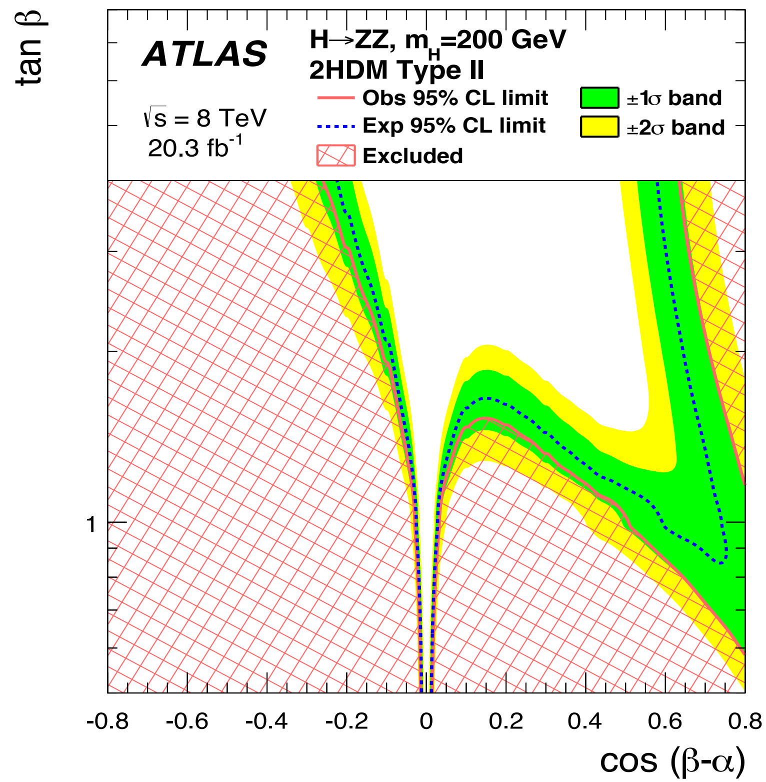
ZZ Results – 2HDM

Type I

arXiv:1507.05930



Type II arXiv:1507.05930



Chosen mH and ranges of tan β and cos(β-α) are limited to region where interference between signal and continuum background is negligible

Conclusions

- ATLAS has performed searches for high mass Higgs up to 1.5 TeV using Run-I 8 TeV data
- No significance excess is found compared with expectations. Upper limits on the cross section times branching ratio are presented
- Run-II data (with higher center-of-mass energy) will be very interesting

Thank You

WW->lvlv

WW->lvlv

The discriminant used to derive the final results in this analysis is the transverse mass m_{T}, defined as:

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}, \tag{2}$$

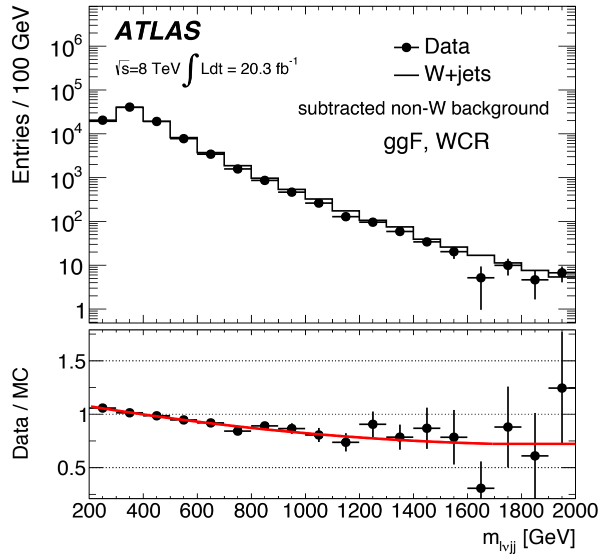
where $E_{\mathrm{T}}^{\ell\ell} = \sqrt{|\mathbf{p}_{\mathrm{T}}^{\ell\ell}|^2 + m_{\ell\ell}^2}$.

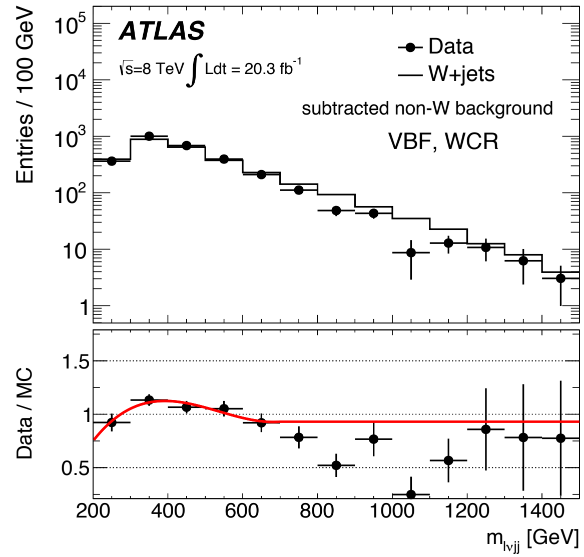
5.2.1 *WW* background

In the $N_{\mathrm{jet}} \leq 1$ categories, the WW background is normalised using a CR defined with the selection summarised in Table 5. To orthogonalise the WW CRs to the $N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ SRs, the selection on $\Delta\eta_{\ell\ell}$ is reversed with respect to the SR definitions: $\Delta\eta_{\ell\ell} > 1.35$ is required. Only the different-flavour final states are used to determine the WW background, and the purity is 70.5% and 40.6% in the $N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ categories, respectively. The normalisation factors obtained from the simultaneous fit to the signal and control regions are 1.18 ± 0.04 for the $N_{\mathrm{jet}} = 0$ CR and 1.13 ± 0.08 for the $N_{\mathrm{jet}} = 1$ CR, where the uncertainty quoted includes only the statistical contribution. The high normalisation factor for WW events with zero jets has been studied in Ref. [84], and results from poor modelling of the jet veto efficiency. The WW prediction in the $N_{\mathrm{jet}} \geq 2$ category is taken from simulation, because it is difficult to isolate a kinematic region with a sufficient number of WW events and a small contamination from the top-quark background.

WW->lvqq : W+jets MC reweighting

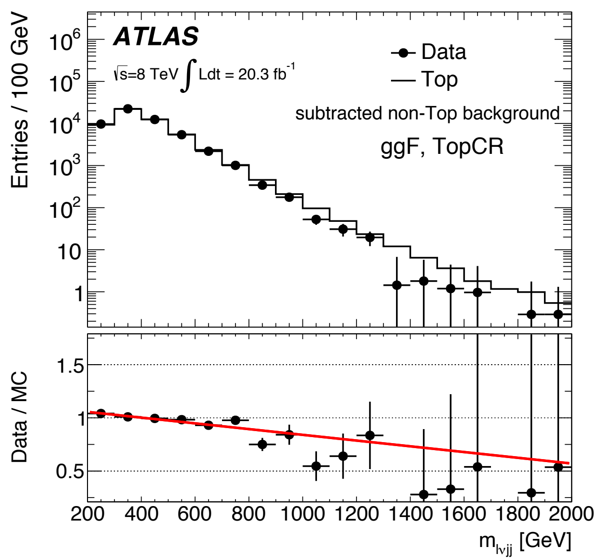
W

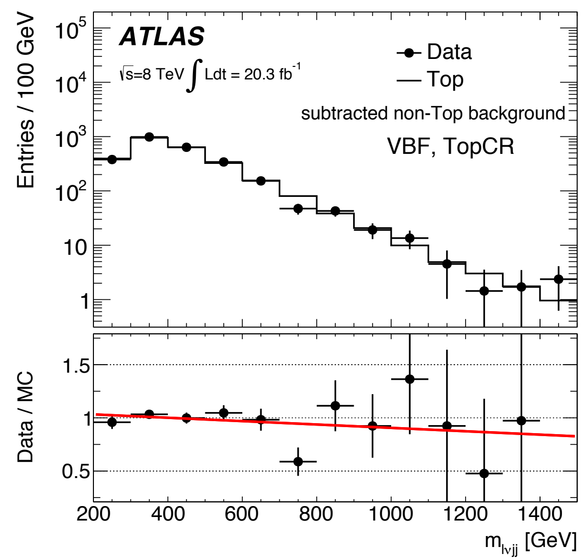




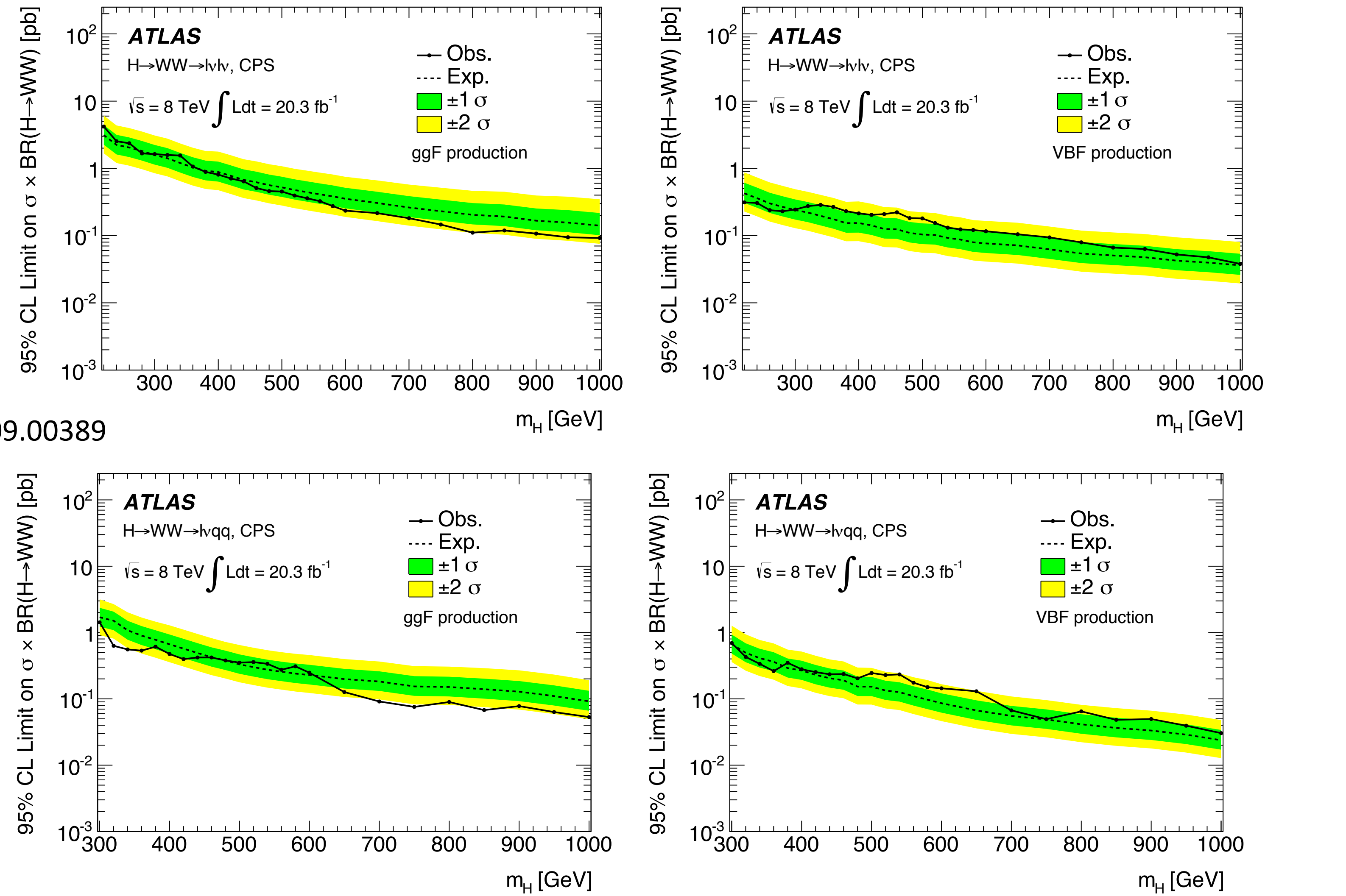
arXiv:1509.00389

Top



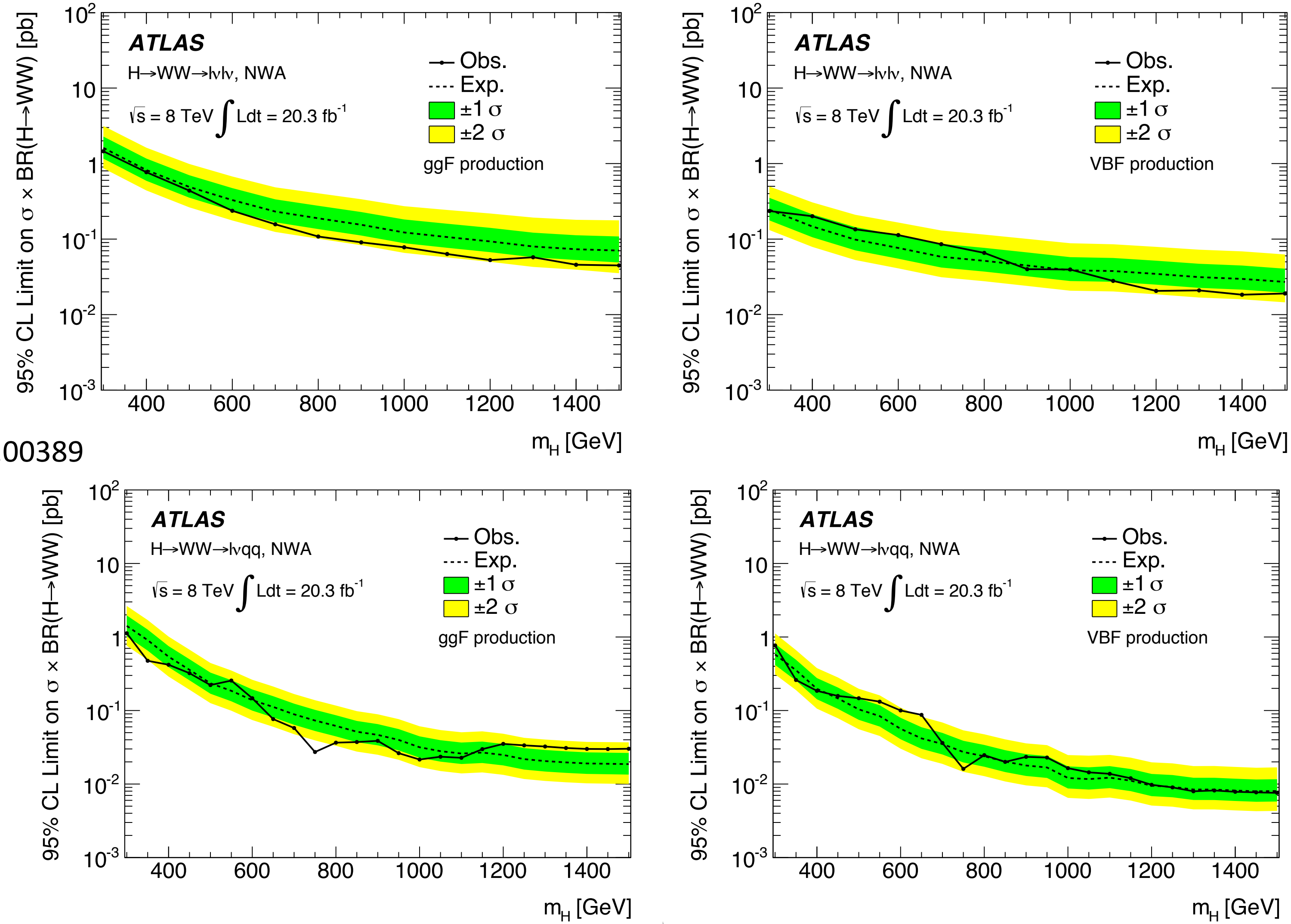


WW : Results from individual channels



arXiv:1509.00389

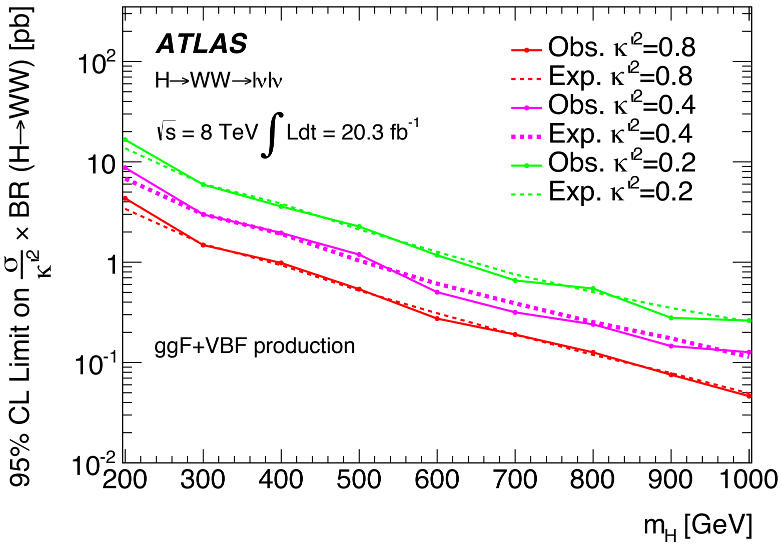
WW : Results from individual channels



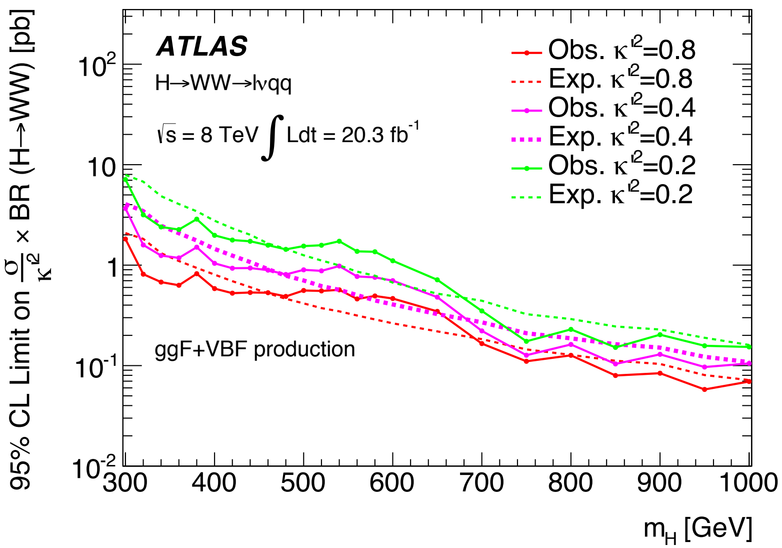
arXiv:1509.00389

WW : Results from individual channels

lvlv



lvqq



arXiv:1509.00389

ZZ

Search		Channel	SR	Z CR	W CR	Top CR
$\ell\ell\ell\ell$	ggF		m_{eeee}, $m_{\mu\mu\mu\mu}$, $m_{ee\mu\mu}$, $m_{\mu\mu ee}$			
	VBF		$m_{\ell\ell\ell\ell}$			
	VH		$m_{\ell\ell\ell\ell}$			
$\ell\ell\nu\nu$	ggF		m_{T}^{ee}, $m_{\mathrm{T}}^{\mu\mu}$			
	VBF		N_{evt}^{ee}, $N_{\mathrm{evt}}^{\mu\mu}$			
$\ell\ell qq$	ggF	untagged	$m_{\ell\ell jj}$	MV1c cat.		$m_{\ell\ell jj}$
		tagged	$m_{\ell\ell jj}$	MV1c cat.		
		merged-jet	$m_{\ell\ell j}$	$m_{\ell\ell j}$		
	VBF		$m_{\ell\ell jj}$	$m_{\ell\ell jj}$		
$\nu\nu qq$	ggF	untagged	m_{T}		MV1c cat. (0 b-tags) MV1c cat. (1 b-tag)	
		tagged	m_{T}			

Table 3: Summary of the distributions entering the likelihood fit for each channel of each search, both in the signal region (SR) and the various control regions (CR) used to constrain the background. Each entry represents one distribution; some channels have several distributions for different lepton flavours. MV1c cat. refers to the MV1c b-tagging event category. The distributions are unbinned for the $\ell\ell\ell\ell$ search and binned elsewhere. The VBF channels of the $\ell\ell\nu\nu$ search use only the overall event counts. See the text for the definitions of the specific variables used as well as for the definitions of the signal and control regions.

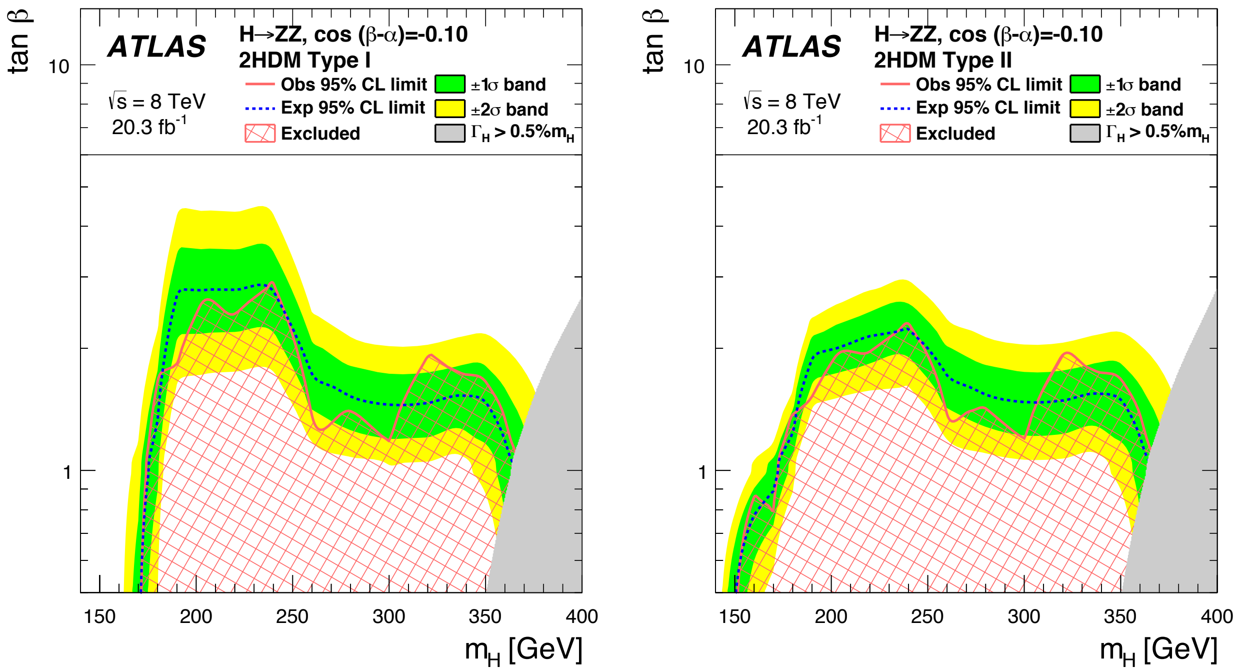
ZZ

ggF mode Systematic source	Effect [%]	VBF mode Systematic source	Effect [%]
m_H = 200 GeV			
$gg \to ZZ$ K-factor uncertainty	27	$gg \to ZZ$ acceptance	13
Z+hf $\Delta\phi$ reweighting	5.3	Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)	13
Luminosity	5.2	$gg \to ZZ$ K-factor uncertainty	13
Jet energy resolution ($\ell\ell qq/\nu\nu qq$)	3.9	Z + jets $\Delta\phi$ reweighting	7.9
QCD scale $gg \to ZZ$	3.7	Jet energy scale η modelling ($\ell\ell qq/\nu\nu qq$)	5.3
m_H = 400 GeV			
$qq \to ZZ$ PDF	21	Z + jets estimate ($\ell\ell\nu\nu$)	34
QCD scale $qq \to ZZ$	13	Jet energy resolution ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	6.5
Z + jets estimate ($\ell\ell\nu\nu$)	13	VBF Z + jets $m_{\ell\ell jj}$	5.5
Signal acceptance ISR/FSR ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	7.8	Jet flavour composition ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	5.3
$Z + b\bar{b}$, $Z + c\bar{c}$, $p_T^{\ell\ell}$	5.6	Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)	4.8
m_H = 900 GeV			
Jet mass scale ($\ell\ell qq$)	7	Z + jets estimate ($\ell\ell\nu\nu$)	19
$Z + jj$ p_T^Z shape ($\nu\nu qq$)	5.6	Jet mass scale ($\ell\ell qq$)	8.7
$qq \to ZZ$ PDF	4.3	$Z + jj$ $p_T^{\ell\ell}$ shape	7.3
QCD scale $qq \to ZZ$	3.5	Jet energy resolution ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	4.4
Luminosity	2.6	Jet flavour composition (VV/Signal)	2.6

Table 4: The effect of the leading systematic uncertainties on the best-fit signal cross-section uncertainty, expressed as a percentage of the total (systematic and statistical) uncertainty, for the ggF (left) and VBF (right) modes at m_H = 200, 400, and 900 GeV. The uncertainties are listed in decreasing order of their effect on the total uncertainty; additional uncertainties with smaller effects are not shown.

ZZ

arXiv:1507.05930



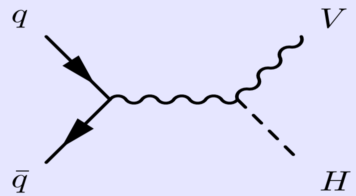
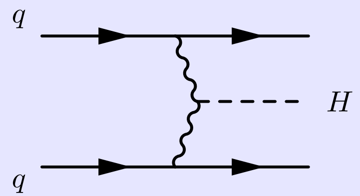
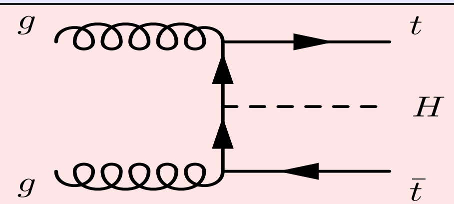
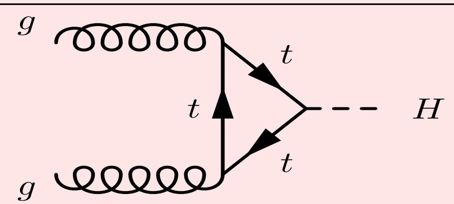
(a) Type-I

(b) Type-II

Figure 14: 95% CL exclusion contours in the 2HDM (a) Type-I and (b) Type-II models for $\cos(\beta-\alpha) = -0.1$, shown as a function of the heavy Higgs boson mass m_H and the parameter $\tan\beta$. The shaded area shows the observed exclusion, with the black line denoting the edge of the excluded region. The blue line represents the expected exclusion contour and the shaded bands the 1-σ and 2-σ uncertainties on the expectation. The grey area masks regions where the width of the boson is greater than 0.5% of m_H. For the choice of $\cos(\beta-\alpha) = -0.1$ the light Higgs couplings are not altered from their SM values by more than a factor of two.

How to probe different production modes

Higgs candidate events are selected from their decay states. Need to disentangle different production modes to probe Higgs couplings

VH		Leptons, missing E_T or low-mass dijets (from W/Z decays) not included in WW or $Z\gamma$ in this talk
VBF		Two forward jets with high di-jet mass and large rapidity gap
ttH		Two top quarks : leptons, missing E_T, multi-jets or b-tagged jets not discussed in this talk
ggF		The rest

Statistical Procedure

Likelihood : Poisson probabilities with parameter of interest (POI) and nuisance parameters.

$$\mathcal{L}(\text{data}|\mu,\theta) = \text{Poisson}(\text{data}|\mu \times s(\theta) + b(\theta)) \times p(\tilde{\theta}|\theta) \tag{1}$$

Signal strength μ is tested with test statistics

$$q_\mu = -2\ln\Lambda(\mu) = -2\ln\{\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})}\} \tag{2}$$

Combined likelihood is the product of likelihoods from different channels,

$$\mathcal{L}(\text{data}|\mu,\theta) = \prod_i \mathcal{L}_i(\text{data}_i|\mu,\theta_i) \tag{3}$$

Global fitting with combined likelihood